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FINAL REPORT

Studies of Periodic Waveguide Structures For Generation and Parametric Interaction of Coherent Optical Waves

by

Shyh Wang

Office of Naval Research

Contracts N00014-75-C-0420
and N000014-69-A-0200-1063

1 March 1973 - 30 June 1977

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This final report is for both contract N000014-69-A-0200-1063 for "Studies of Periodic Waveguide Structures for Generation and Parametric Interaction of Coherent Optical Waves" (March 1, 1973 - February 28, 1975) and contract N00014-75-C-0420 for "Continuation of Research Involving the Studies of Periodic Waveguide Structures for Generation and Parametric Interaction of Coherent Optical Waves" (March 1, 1975 - June 30, 1977). During the two contract periods, we made a number of important contributions to the basic understanding and technological development of integrated optical devices using periodic waveguides. For a detailed discussion of the accomplishments, please refer to the published papers (see the attached list of publications). A summary of the highlights is given below.

A possible laser source for integrated optics must meet two requirements: (1) being capable of integration with other optical components and (2) providing adequate wavelength selectivity for single-mode operation. The DFB (distributed-feedback) laser with the periodic waveguide in the active region has its disadvantages. In a series of papers, we first proposed a novel laser structure, the DBR (distributed Bragg-reflector) laser, with the periodic waveguides placed in the passive (umpumped) regions (paper 1) and then made theoretical investigations analyzing and comparing the expected performances of the DFB and the DBR laser (papers 1, 3, 4, 6, 7 and 8). From the analyses and a careful examination of the two lasers, it was concluded that the DBR laser should offer more promising laser performance and more flexibility for integration. Based on this conclusion, we concentrated our research exclusively on the DBR laser.

In the meantime, we also built our experimental capabilities for LPE

(liquid-phase epitaxy) growth of GaAs-(GaAℓ)As films and for fabrication of periodic (grating) structures. A number of novel techniques were developed, including the simultaneous exposure and development technique for sharpening the contrast in photoresist (papers 2, 5 and 13), the use of preferential chemical etching for making gratings (paper 10), the thin-film prism (paper 9) and the formation of various two-dimensional waveguiding structures over preferentially chemically etched channels (papers 12 and 14). The work discussed in paper 14 is important since it provides a simple means of fabricating two-dimensional waveguides which are needed for control of lateral modes in injection lasers. As a result of this effort, we recently have been able to achieve (1) linear output versus current relation, (2) spatial stability of mode pattern, (3) single-mode operation, and (4) suppression of relaxation oscillation in a novel injection laser we called the CJSF laser [see Figueroa and Wang, Appl. Phys. Lett., Vol. 32, 85 (1978)]. The CJSF work is being supported by NSF and ARO.

Our continuing effort in building up the experimental capabilities has enabled us to be in the forefront of semiconductor laser research. Besides the work on the CJSF laser, we reported the first operation of the DBR laser, both optically pumped (paper 17) and injection-pumped (paper 15), and the half-ring laser (paper 18). As mentioned earlier, one important objective of the DBR laser is the integration of the laser with other optical components. This problem was carefully examined and a solution for overcoming re-absorption in the passive region was proposed (papers 19 and 21). After the examination it was evident that a structure employing separate optical and carrier confinement in the form of a LOC (large optical cavity) structure would serve the purpose.

It became equally evident that only the DBR laser but not the DFB laser could use the LOC structure to provide a continuous waveguide upon which other optical components could be built. This effort has been very successful. Recently we have been able to integrate the DBR laser with a detector (Shams, Namizaki, and Wang to be published in Appl. Phys. Lett., Feb. 1978) and the DBR laser with an intensity modulator (Shams, Namizaki, and Wang, to be published in Appl. Phys. Lett., Mar. 1978). The LOC-DBR work is being supported by NSF and ARO.

In summary, the support we received from the Office of Naval Research had enabled us to move ahead in several fronts in semiconductor laser
The report summarizes
research. We have made important contributions in the realization of the DBR laser for integrated optics and in the achievement of "kink-free" injection lasers. These efforts would not be possible without the initial support from ONR. We are looking forward to a renewance of this fruitful relationship.

Graduate Students

R. F. Cordero (Ph.D., June 1975) "Studies of Thin Film Periodic Waveguides for Distributed Feedback Lasers"

C. C. Tseng (Ph.D., September 1976) "Integrated-Optics Thin-Film Devices"

D. G. Meyer (M.S., September 1977) "Chemical and Electrical Characteristics of an Anodically Grown Native Oxide of GaAs"

List of Publications

1. "Principles of Distributed Feedback and Distributed Bragg Reflector Lasers," J. Quantum Electron., Vol. QE-10, p. 413 (1974).

2. "Simultaneous Exposure and Development Technique for Making Gratings on Positive Photoresist," Appl. Phys. Lett., Vol. 24, p. 196 (1974) (with W. T. Tsang).

3. "Threshold Condition for Thin-Film Distributed-Feedback Lasers," Appl. Phys. Lett., Vol. 24, p. 474 (1974) (with R. F. Cordero).
4. "Analysis of Distributed Feedback and Distributed Bragg-Reflector Laser Structures by Method of Multiple Reflections," J. Appl. Phys., Vol. 45, p. 3975 (1974) (with R. F. Cordero and C. C. Tseng).
5. "Grating Masks Suitable for Ion-Beam Machining and Chemical Etching," Appl. Phys. Lett., Vol. 25, p. 415 (1974) (with W. T. Tsang).
6. "Thin-Film Bragg Lasers for Integrated Optics," Wave Electronics, Vol. 1, p. 31 (1974).
7. "A Thin-Film Ring Distributed Feedback Laser," J. Appl. Phys., Vol. 46, p. 89 (1975).
8. "Energy Velocity and Effective Gain in Distributed Feedback Lasers," Appl. Phys. Lett., Vol. 26, p. 89 (1975).
9. "A Thin-Film Prism as a Beam Splitter for Multimode Guided Waves in Integrated Optics," Optics Communications, Vol. 13, p. 342 (1975) (with C. C. Tseng and W. T. Tsang).
10. "Preferentially Etched Diffraction Gratings in Silicon," J. Appl. Phys., Vol. 46, p. 2163 (1975) (with W. T. Tsang).
11. "Integrated Grating-Type Schottky-Barrier Photodetector with Optical Channel Waveguide," Appl. Phys. Lett., Vol. 26, p. 632 (1975) (with C. C. Tseng).
12. "Optical Bends and Rings Fabricated by Preferential Etching," Appl. Phys. Lett., Vol. 26, p. 699 (1975) (with C. C. Tseng and D. Botez).
13. "Experimental Studies of Photoresist Gratings," Wave Electronics, Vol. 1, p. 85 (1975) (with W. T. Tsang).
14. "Growth Characteristics of GaAs-$Ga_{1-x}A\ell_xAs$ Structures Fabricated by

Liquid-Phase Epitaxy over Preferentially Etched Channels," Appl. Phys. Lett., Vol. 28, p. 234 (1976) (with D. Botez and W. T. Tsang).

15. "GaAs-$Ga_{1-x}A\ell_xAs$ Double-Heterostructure Injection Lasers with Distributed Bragg Reflectors," Appl. Phys. Lett., Vol. 28, p. 596 (1976) (with W. T. Tsang).

16. "Sputtered-Etched Ta_2O_5 Corrugation Gratings for DFB Lasers," Wave Electronics, Vol. 1, p. 355 (1976) (with R. F. Cordero).

17. "Optically Pumped Epitaxial GaAs Waveguide Lasers with Distributed Bragg Reflectors," IEEE J. Quantum Electron., Vol. QE-12, p. 549 (1976) (with C. C. Tseng and D. Botez).

18. "Optically Pumped GaAs-$Ga_{1-x}A\ell_xAs$ Half-Ring Laser Fabricated by Liquid-Phase Epitaxy over Chemically Etched Channels," Appl. Phys. Lett., Vol. 29, p. 502 (1976) (with D. Botez and L. Figueroa).

19. "Design Considerations of the DBR Injection Laser and the Waveguiding Structure for Integrated Optics," IEEE J. Quantum Electron., Vol. QE-13, p. 176 (1977).

20. "Broadening of the Longitudinal Modes due to Transient Heating in Optically Pumped Semiconductor Lasers," J. Appl. Phys., Vol. 48, p. 1995 (1977) (with L. Figueroa and D. Botez).

21. "Distributed-Bragg Reflector Injection Lasers for Integrated Optics," NATO Symposium Proceedings on Optical Fibers, Integrated Optics, and their Military Applications, p. 21-1 (1977).

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